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by

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ABSTRACT

Pioneer 7 passed through the downstream region of solar wind interaction with the geomagnetic field at 900-1050 R_E during September 26 to October 3, 1966. Detailed measurements of the magnetic field suggest that certain of the magnetic lines of force connect to the earth through the geomagnetic tail. A coherent, well-ordered tail with imbedded neutral sheet does not appear to have been observed. This suggests that the geometry of the tail changes to a complex set of intermingled filamentary flux tubes at several hundred R_E.

Introduction

The NASA deep space probe Pioneer 7 was launched from the Eastern Test Range, Cape Kennedy, Florida on August 17, 1966 at 15:20:07 UT. The principal objective was to place the spin stabilized spacecraft into a heliocentric orbit which would range between 1.0 and 1.1 AU lagging behind the earth with respect to heliocentric longitude. A secondary objective and one which influenced the selection of the specific firing time was to have the trajectory pass near the sun-earth line and at as close a distance to the earth as consistent with aphelion at 1.1 AU. The purpose of this shaping of the trajectory was to investigate the possible extent of the geomagnetic tail (Ness, 1965) or detectable wake affects associated with the solar wind interaction with the geomagnetic field. Previous measurements on the Mariner 4 spacecraft (Van Allen, 1965) on a trajectory to Mars did not reveal any fluctuations in the flux of energetic particles ($E_e > 45$ Kev) associated with the terrestrial tail or wake at a geocentric distance of 21 X 10^6 kilometers (3300 R_E; 1 R_E = 6378.2 km). See Dessler (1966) and Van Allen (1966) for discussions of the significance of these data.

The investigations of the geomagnetic tail at lunar distances by Luna 10 (Gringauz et al, 1966; Grigorov et al, 1966; Zhuzgov et al, 1966) present a somewhat inconsistent result. Interpretations of the plasma and particle experiments indicate the existence of the geomagnetic tail and neutral sheet during full moon periods while the magnetic field measurements lead to the conclusion that it is absent. Magnetic field measurements by Explorer 33 (Ness et al, 1967) have demonstrated the existence of the tail and its imbedded neutral sheet at distances up to 0.5 X 10^6 Kms ($80R_E$). A reinterpretation of the Luna 10 magnetic field results necessitated by these conflicting reports has been presented by Ness (1967).

This note discusses the results of an initial study of the data obtained by the NASA/Goddard Space Flight Center magnetic field experiment on Pioneer 7 during the time interval from September 23 to October 3, 1966 which included the period during which the tail might have been expected to be observed. The length of the magnetospheric tail has been estimated by Dungey (1965) and Dessler (1964) to range from approximately 1,000 R_E to several AU. A simple model of the tail has been used to determine the time period during which tail related phenomena might be expected. It is assumed that the geomagnetic tail is approximately 40 R_E in diameter (Ness, 1965; Ness et al, 1967) and that the direction of the solar wind flow appears to be aberrated by 3° to 5° due to the heliocentric motion of the earth. These assumptions yield the region, indicated in Figure 1 by shading, during which a highly collimated, well ordered and rigidly structured geomagnetic tail would have been observed. The spacecraft does not lie close to the ecliptic plane however, ranging from 24 to 28 R_E above it, as indicated in Figure 1, by Z_{SE}.

The magnetic field experiment on Pioneer 7 is similar to that instrumented for the Pioneer 6 spacecraft (Ness et al, 1966). Briefly, a mono-axial fluxgate magnetometer sensor oriented at 54° 45' to the spin axis is sampled three times during one revolution of the spacecraft so that an orthogonal set of measurements is obtained in 0.656 seconds, the spin period = 0.984 seconds. The sensitivity of the experiment has been improved by a factor of 2 over that of Pioneer 6. Quantization uncertainties due to the on-board analog-to-digital converter yield a precision in each component measurement of ± 0.126 gamma. The zero level of the sensor has been verified by inflight reorientation and the accuracy of the data is limited only by quantization and the spacecraft associated magnetic fields. An analysis of these error sources indicates that the nominal accuracy of the experiment is ± 0.2 gamma.

Observations

The data to be discussed in this initial report represent averages of the magnetic field computed over time intervals of 30 seconds or 1 hour. The spacecraft transmitted data at a rate of 512 bps during the interval of interest and this permitted sampling of the magnetic field vector, on average, once every 1.3 seconds. Thus during each 30 second interval, 23 sets of individual orthogonal component measurements were linearly averaged and employed to construct an average vector field magnitude and direction in solar ecliptic coordinates. The RMS deviation of the individual component measurements during the 30 second interval has also been computed and is included to reveal the presence of fluctuations of the magnetic field in each interval. During much of the data to be discussed in this note the RMS deviation is observed to be close to the expected quantization error of 0.13 gamma. At times, however, the RMS deviation rises to 1 or even 2 gamma, particularly when the magnetic field direction changes abruptly.

Hourly averages of the magnetic field have been computed from the 30 second data averages. Again the process of linearly averaging the orthogonal components and constructing an equivalent vector magnetic field has been employed. A measure of the fluctuation of the magnetic field during each hour can be deduced by comparing the magnitude of the field obtained by linearly averaging the individual magnitudes of the 30 second sample points with the magnitude obtained from the component averages. The observed magnetic fields on

Pioneer 7 for the period of interest are summarized in Figures 2 and 3. The difference between the two magnitude averages, indicated by shading, depends upon the fluctuations of the ambient magnetic field. It is noted that throughout the time interval the magnetic field is less than 16 gammas and generally greater than 4 gamma. The field tends to be directed close to the plane of the ecliptic at an angle $\phi_{SE} = 270^\circ$ to 360°.

Throughout this time interval terrestrial magnetic activity, as measured by the Kp index, was relatively low with values of approximately 2 to 4. Two events classified as sudden commencements have been reported by the preliminary HAO Bulletin. These occurred on September 23 at 0856 UT and September 27 at 1530 UT. Following these events it is noted that the magnetic field magnitude generally rises for a day or so. The data is rather similar to the measurements for other times on Pioneer 7 and it is clear from inspection of these data that there are seldom intervals during which the magnetic field is both steady and directed either parallel or anti-parallel to the earth-sun line as would be expected with a collimated geomagnetic tail fully developed as predicted by Dessler (1964). However, the direction of solar wind flow is known to be variable with respect to the earth-sun line by as much as 5° to 10° (Strong et al, 1965; Wolfe et al, 1966). Thus it is to be expected that the changing solar wind direction will change the tail orientation and cause the tail to be swept over the satellite trajectory for variable intervals of time. If such is the case, however, the data shown in Figures 2 and 3 indicate that such time intervals are generally of a duration less than one hour. The time interval 1700-1800 September 27 is an example of one hour when detailed data suggests that the tail field is observed.

An inspection of the detailed 30 second average data has been performed in an attempt to identify shorter intervals of time during which the orientation of the field closely parallels the earth-sun line. The result of this study has shown that there are time intervals during which the magnetic field direction closely parallels the earth-sun line and increases generally to between 6 to 8 gamma with relatively weaker fields on other occasions. In certain instances, to be discussed subsequently, rapid changes of the orientation occur in which the field changes from being directed towards the sun to away from the sun. Multiple reversals several times suggest the detection of the imbedded neutral sheet in the geomagnetic tail.

Figure 4 presents the magnetic field measurements on September 25 when anomalous plasma conditions were reported by Wolfe et al (1967). During this two hour interval the periods when disturbed plasma conditions were observed is indicated. It is seen that these periods generally correspond to intervals when the magnetic field magnitude is approximately 8 gamma, larger than the fields at other times during the same period. In addition, fluctuations of the field, as measured by the RMS values (ΔX, ΔY, ΔZ) all indicate rapid fluctuations of the field as the magnitude and/or direction changes rapidly. For the time interval from 1851 to 1921 the field is directed approximately in the plane of the ecliptic ($\theta = 0 \pm 10^o$) at an angle of $315^o \pm 15^o$

to the earth-sun line. At this time an absence of plasma or very weak plasma flux is reported with a following change in the plasma spectrum. A small flux is observed when the direction of the field closely parallels the earth-sun line between 1941 to 1946. These data illustrate general features of the detailed magnetic field observations although they do not best illustrate and suggest the presence of the extended geomagnetic tail field.

Data revealing the possible presence of the tail field over more extended periods is shown in Figure 5. During this three hour time interval the field is observed usually to be directed close to the plane of the ecliptic, and to be directed either towards the sun or away from the sun but always closely paralleling the earth-sun line. Abrupt changes in the direction of the field are observed near 1601, 1620 and 1638 with very rapid fluctuations in the direction of the field observed between 1609 to 1619. It is noted that the magnitude usually varies coherently with the direction of the field, being largest when the field is stable in direction and high frequency fluctuations are absent, as indicated by very low values of the RMS deviations. The possible position of the neutral sheet is indicated in the figure for times when the field abruptly changes direction. These data are the most characteristic of the probable detection of the geomagnetic tail field at these distances by Pioneer 7.

A final example of detailed data is shown in Figure 6 for September 30 when the interesting feature of abrupt changes in direction of the tail field characteristic of multiple traversals of the neutral sheet are again observed during a two hour interval. Generally the tail presence is determined by the existence of a magnetic field of 6 to 8 gamma at an orientation ($\phi = 175^{\circ} \pm 5^{\circ}$; $\phi = 355^{\circ} \pm 5^{\circ}$) closely paralleling the earth-sun line. The sense is dependent upon whether the spacecraft is immersed in the tail fields which originate from the North or South polar cap regions of the earth.

Conclusions

It is suggested that the orientation and magnitude changes of the magnetic field observed when the Pioneer 7 spacecraft was in the region of the expected geomagnetic tail are consistent with some of the field lines being connected to the earth through the geomagnetic tail. However, the cross-sectional geometry of the tail is difficult to assess because of the relatively short periods of time during which the geometry of the field lines appears to be that required for tail connection. The magnitude of the field is observed from 6 to 8 gamma and is consistent with the value obtained by the Explorer 33 measurements (Ness et al, 1967). Since the solar plasma flow generally is non-radial and changes with time it is to be expected that the geomagnetic tail could be swept over the spacecraft for intervals of time varying from minutes to hours. This is consistent with the observations obtained with the magnetic field experiment, which indicate the existence of geomagnetic tail field lines for variable periods of time.

The existence of abrupt field reversals may indicate the presence of an imbedded neutral sheet whose properties are similar to those observed close to the earth (Ness, 1965; Speiser and Ness, 1967). The presence of field reversals was not expected to be observed since the spacecraft was generally well above the ecliptic plane. However, an out of the ecliptic flow of solar plasma by as little as 1^{o} is sufficient to raise the axis of the tail by 16 R_E at the Pioneer 7 distance of 900 → 1050 R_E. Thus with the known variations in solar plasma flow it is to be expected that field lines originating both in the northern and southern hemisphere polar cap regions of the earth would be observed.

It has been noted in the study of the magnetic field data that generally the observations of the tail and particularly the field reversal regions usually occur between 1500 to 2100 UT. It is possible that the rocking of the inclination of the neutral sheet plane due to the wobbling of the non-axial geomagnetic dipole might be the source of this apparent periodicity in tail observations. A study of the inclination of the solar magnetospheric equatorial plane and the geomagnetic latitude of the subsolar point is presented in Figure 7. It is seen that the direction of the magnetic axis is such that for the observations by Pioneer 7 the neutral sheet is oriented favorably for detection by a spacecraft 25 R_E above the ecliptic plane. In addition, the geomagnetic latitude of the subsolar point is positive and thus also is favorable for tail observations above the ecliptic plane. The maximum inclination of the neutral sheet of -34° is seen to occur at about 1100 UT. The time delay in subsequent observation of the field reversals by Pioneer 7 is consistent with the expected plasma velocities.

It is possible that the geomagnetic tail at these large distances is no longer composed of two separate bundles of oppositely directed field lines separated by a single neutral sheet. Indeed the tail may be separated into a number of filaments in close proximity and intertwined, which while still maintaining connection to the earth no longer preserve the well defined cross-sectional tail geometry observed in cislunar space. Diffusion of plasma from the neutral sheet and the magnetosheath into the geomagnetic tail must be an important process in modifying the geometry and the physical parameters from those observed in near earth regions.

It is anticipated that detailed comparison with the results of simultaneous plasma data, and review of the geometry and the physical parameters obtained from these comparisons shall indicate more precisely the correct nature of the geomagnetic tail at these distances.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1 Trajectory of Pioneer 7 during September 23 to 30, 1966 projected on ecliptic plane during passage through syzygy. The shaded region indicates the time interval during which the geomagnetic tail was expected to be observed assuming the theoretical model described in the text.

Figure 2 Hourly averaged magnetic field observations on Pioneer 7 presented in solar ecliptic coordinates for the period September 23.5 to 28.5, 1966. The two curves for the magnitude represent different methods of computation and their differences reflect fluctuations of the direction and/or magnitude during the hour. (See text).

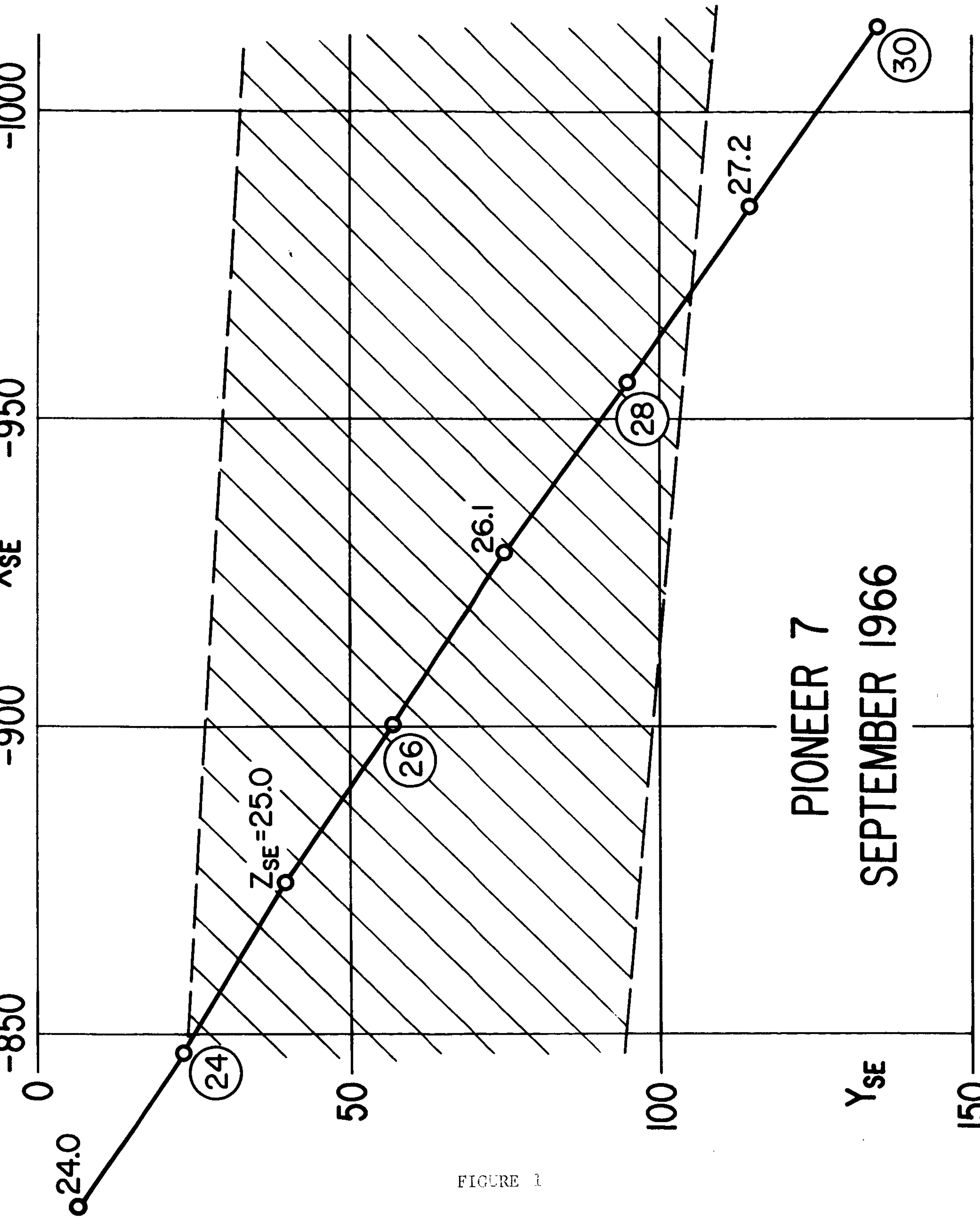
Figure 3 Hourly averaged magnetic field observations on Pioneer 7 presented in solar ecliptic coordinates for the period September 28.5 to October 3.5, 1966. See Figure 2 caption.

Figure 4 Detailed 30 second averaged magnetic field observations by Pioneer 7 on September 25, 1966 when the field orientation, magnitude and plasma flux parameters change due to possible immersion in the extended geomagnetic tail. (See text).

Figure 5 Detailed 30 second averaged magnetic field observations by Pioneer 7 on September 27, 1966 when the field orientation and its rapid reversals are characteristic of the neutral sheet region of the geomagnetic tail. Throughout the 3 hour interval from 1500 to 1800 the field is observed to be directed either away from the sun ($\phi = 180^{\circ}$) or towards the sun ($\phi = 360^{\circ}$).

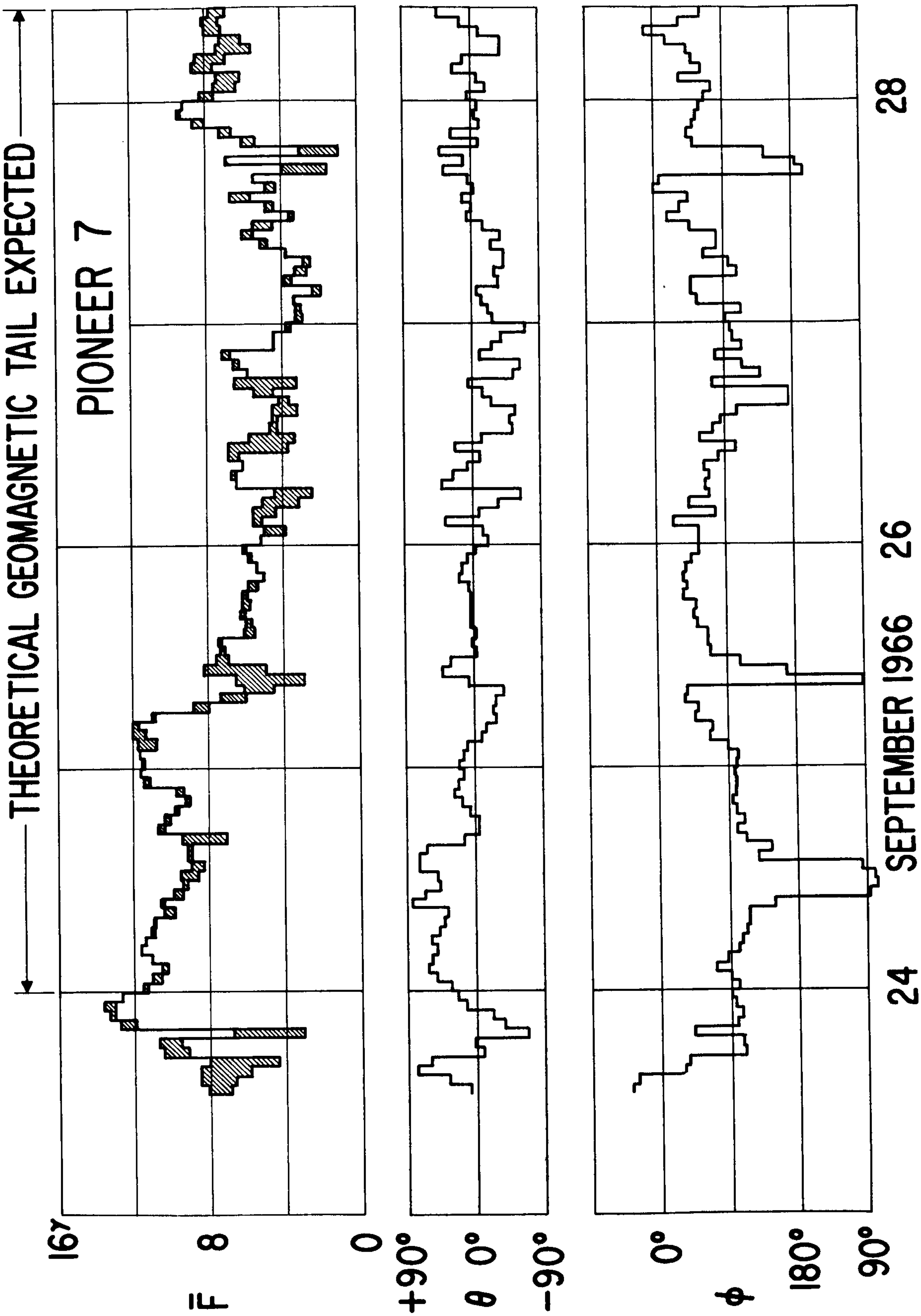
Figure 6 Additional detailed observations of the extended geomagnetic tail on September 30, 1966 with field reversals occurring several times within the two hour interval from 1700 to 1900.

Figure 7 Variation of the inclination (α) of the solar-magnetospheric equatorial plane to the ecliptic plane as a function of time for the interval September 26, 1966 to October 1, 1966. Also the geomagnetic latitude of the subsolar point is presented.



X_{SE}
-850
-900
-950
-1000
Y_{SE}
0
50
100
150
24.0
24
Z_{SE}=25.0
26
26.1
28
27.2
30
PIONEER 7
SEPTEMBER 1966

FIGURE 1



THEORETICAL GEOMAGNETIC TAIL EXPECTED
PIONEER 7
16γ
F 8
0
+90°
θ 0°
-90°
0°
φ
180°
90°
24
26
28
SEPTEMBER 1966

FIGURE 2

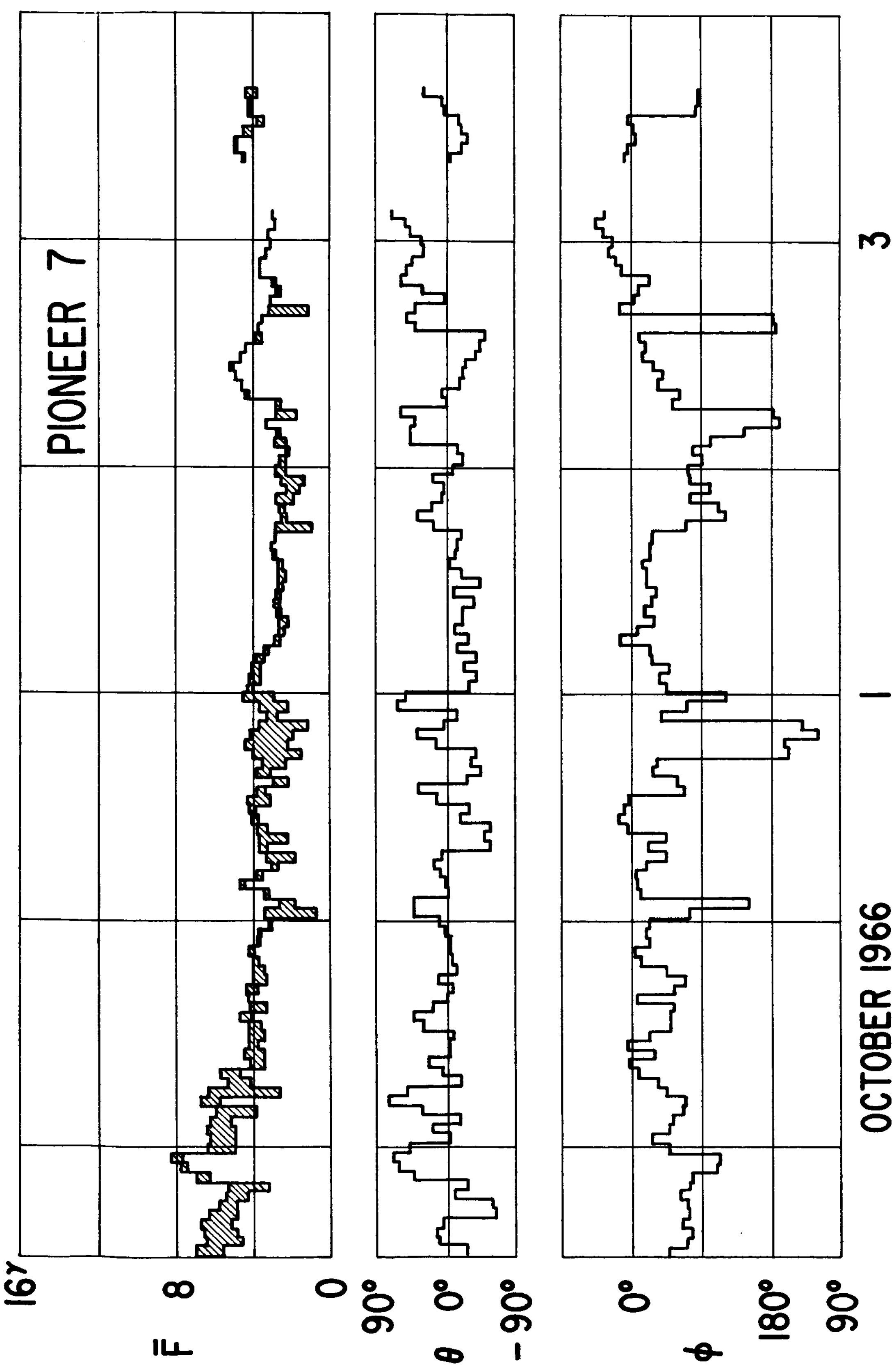
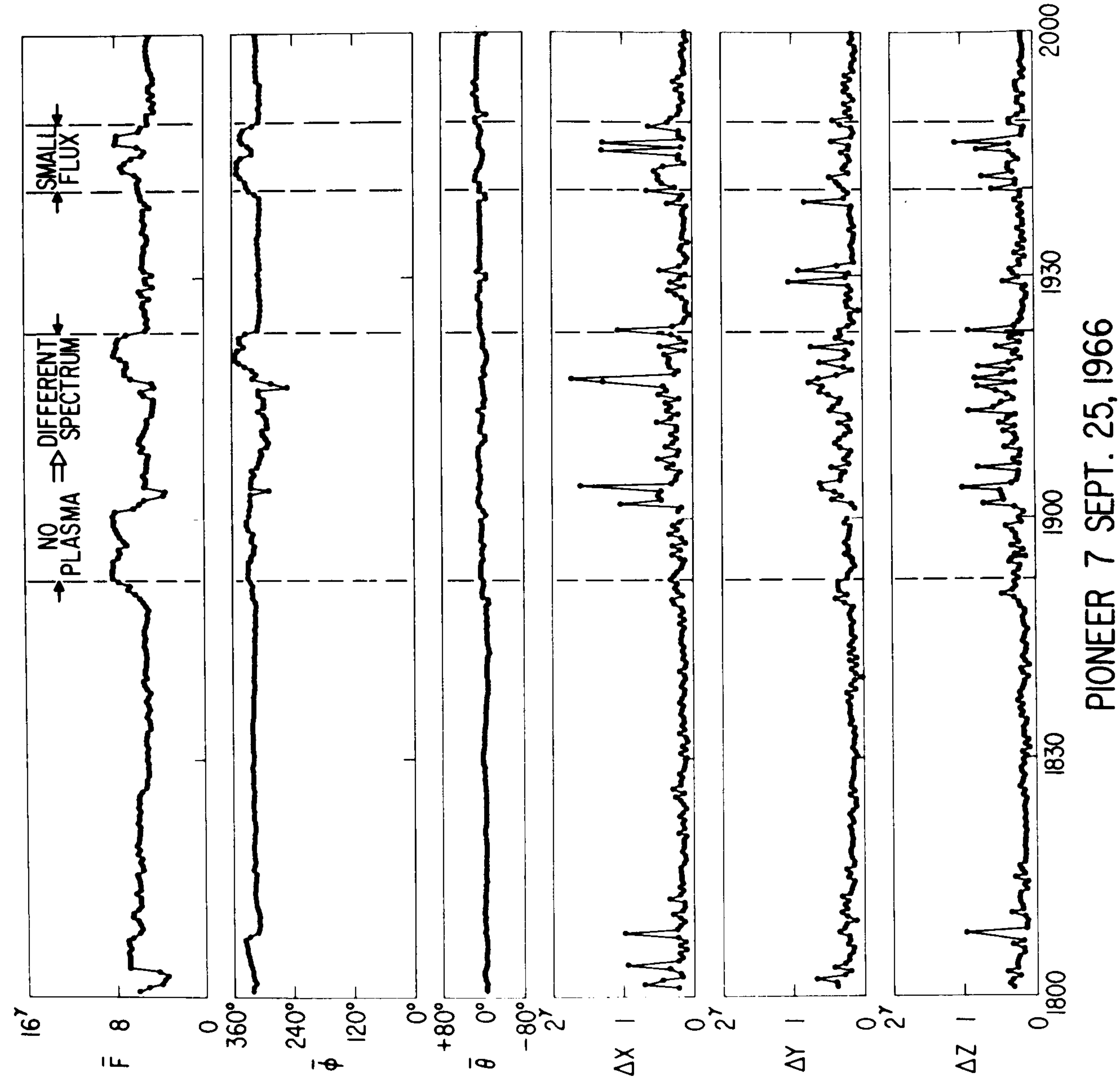


FIGURE 3



PIONEER 7 SEPT. 25, 1966
NO PLASMA
DIFFERENT SPECTRUM
SMALL FLUX
1800
1830
1900
1930
2000
ΔX
ΔY
ΔZ
360°
240°
120°
0°
+80°
-80°

FIGURE 4

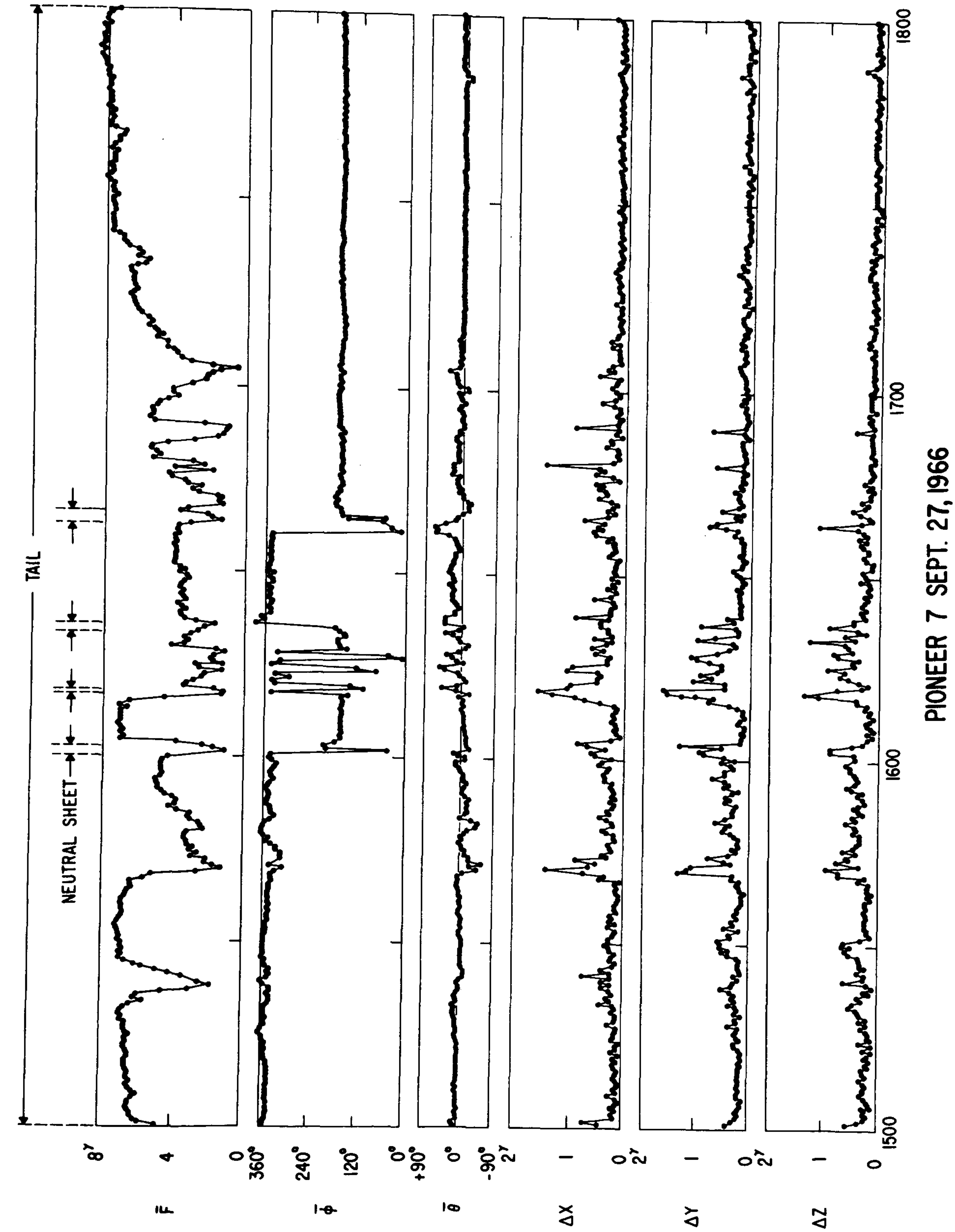
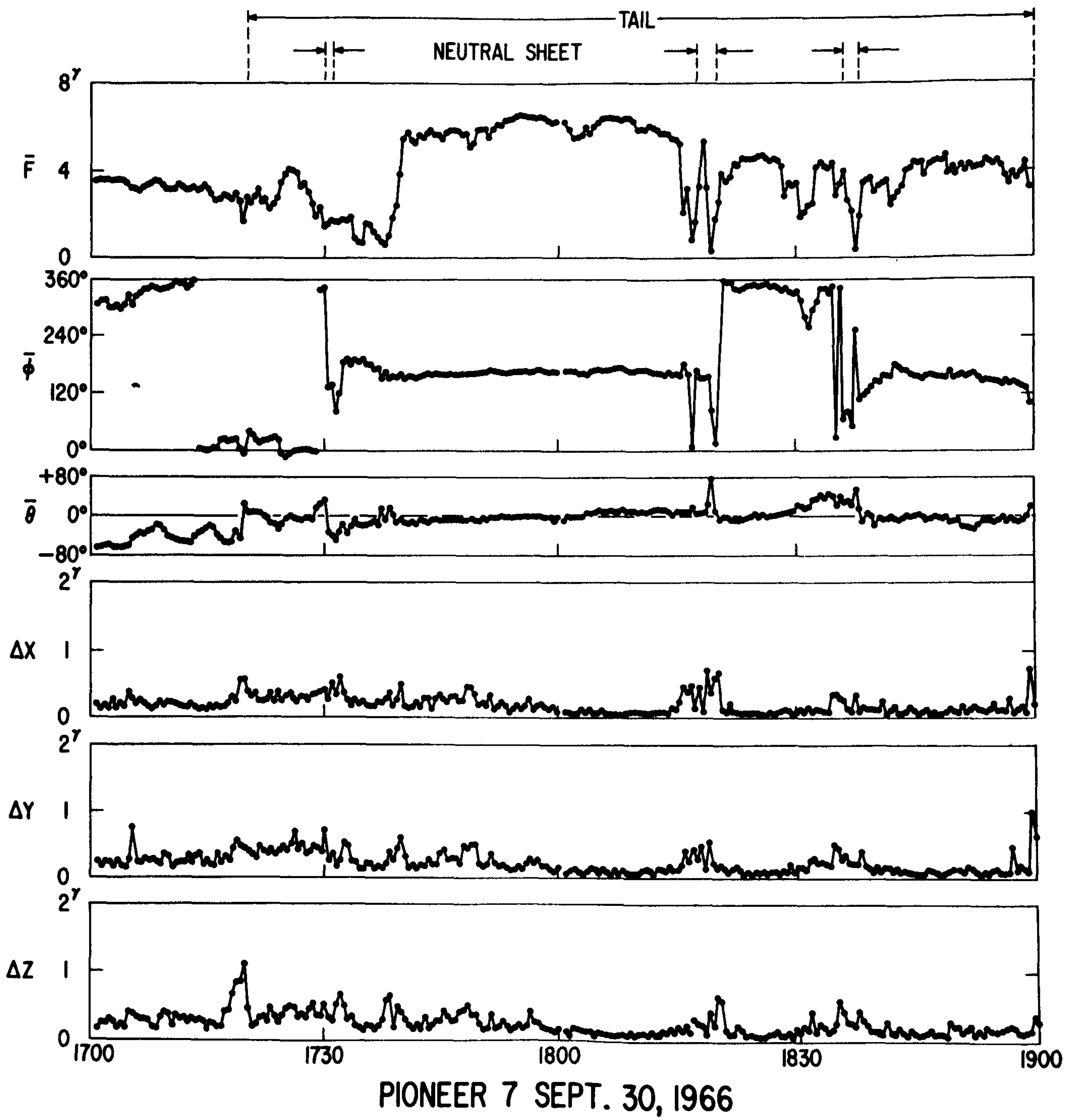

PIONEER 7 SEPT. 27, 1966
TAIL
NEUTRAL SHEET
F
Φ
θ
ΔX
ΔY
ΔZ
1500
1600
1700
1800

FIGURE 5



TAIL
NEUTRAL SHEET
8γ
F̄
4
0
360°
240°
φ̄
120°
0°
+80°
θ̄
0°
−80°
2γ
ΔX
1
0
2γ
ΔY
1
0
2γ
ΔZ
1
0
1700
1730
1800
1830
1900
PIONEER 7 SEPT. 30, 1966

FIGURE 6

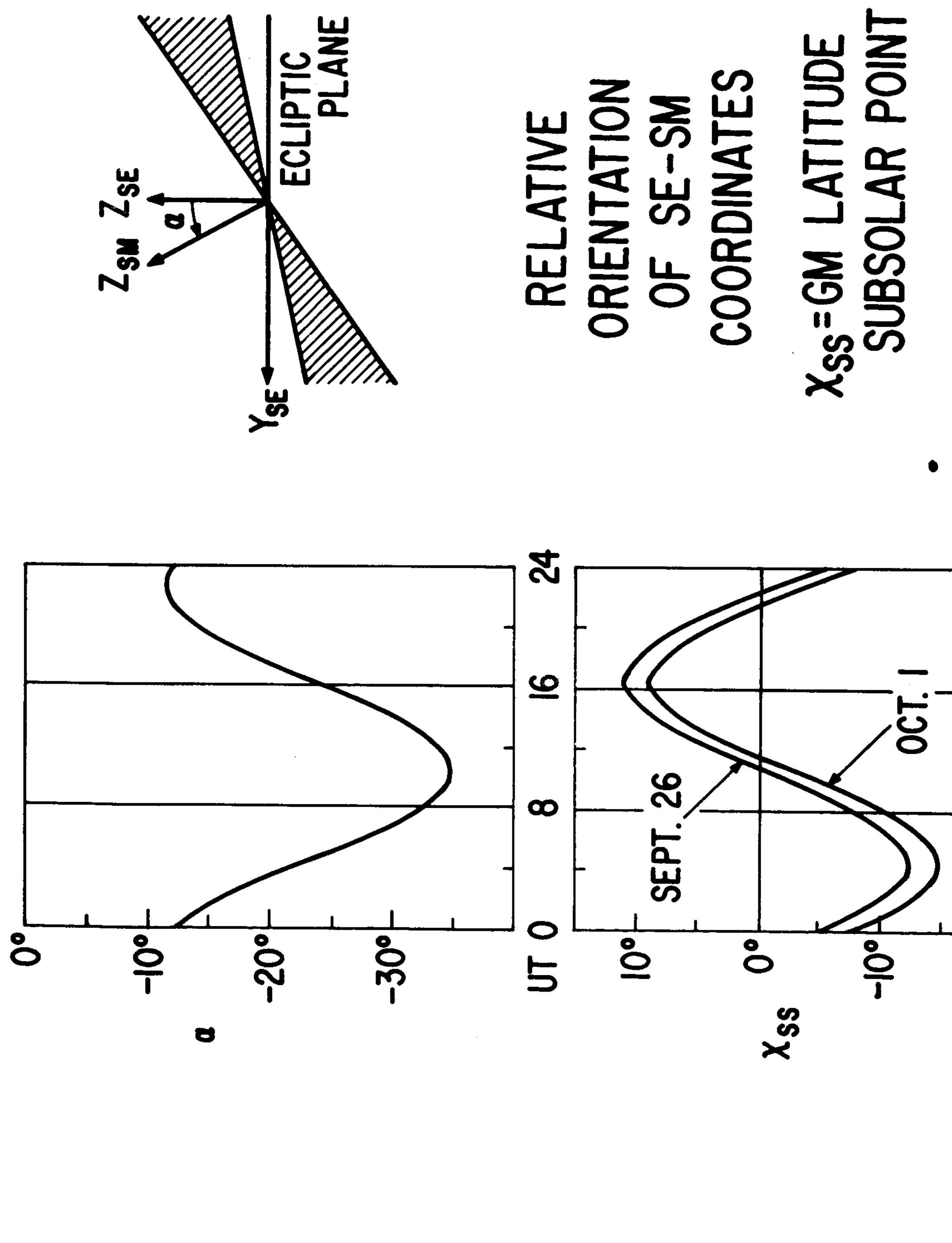

RELATIVE ORIENTATION OF SE-SM COORDINATES
X_{SS} = GM LATITUDE SUBSOLAR POINT
Z_{SM}
Z_{SE}
α
Y_{SE}
ECLIPTIC PLANE
α
0°
-10°
-20°
-30°
UT 0
8
16
24
X_{SS}
10°
0°
-10°
-20°
SEPT. 26
OCT. 1

FIGURE 7